

SAWE Paper No. 3001  
Category No. 10

TECHNOLOGY EVALUATION VIA LOSS MANAGEMENT MODELS  
FORMULATED IN TERMS OF VEHICLE WEIGHT

or

WHITHER A SCHEME FOR VEHICLE FUEL WEIGHT ACCOUNTABILITY?

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For Presentation at the  
59<sup>th</sup> Annual Conference  
of  
Society of Allied Weight Engineers, Inc.  
St. Louis, Missouri June 5-7, 2000

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## Summary

Mass properties engineering is today an established field and an indispensable part of the aerospace vehicle design process. Detailed bookkeeping schemes have been developed to track constituent component weights in extreme detail, down to the last rib and rivet. Given this situation, it may be more accurate to refer to this field as “empty weights engineering” because the focus has always been primarily on management and tracking of vehicle empty weight. Meanwhile, one of the largest weight fractions, fuel weight, is bookkept in a single lump and largely ignored (except inasmuch as it impacts vehicle size and growth factor). It is intuitively obvious that the aerothermodynamic losses due to the engine, airframe systems, and aerodynamic drag of the vehicle are the fundamental drivers on fuel weight and should therefore be expressible as increments in fuel weight chargeable to each loss mechanism. The sum of all chargeable fuel weights is equal to the total fuel weight required to complete a prescribed mission.

The intent of this paper is to formulate a method for quantifying thermodynamic performance in terms of mission fuel chargeable to each thermodynamic loss mechanism. This is then used in conjunction with known vehicle zero fuel weight groups to estimate the gross weight chargeable to each functional component of the vehicle. The results show that chargeable vehicle gross weight can be used as a common figure of merit linking mass properties and performance aspects of vehicle design.

This method is then demonstrated for a Northrop F-5E aircraft, and the fuel weight breakdown is analytically calculated for the design mission. The results of this analysis show that 37.3% of the F-5E subsonic mission fuel requirement is due to propulsion system losses, 36.8% is chargeable to aerodynamic drag, and 24.3% is chargeable to vehicle empty weight. This translates into a chargeable fuel cost of roughly \$173.90, \$171.76, and \$113.53 for each of these three loss mechanisms, respectively. Finally, the usefulness of this technique as a means of technology evaluation is considered. The strengths of this method are that it allows quantification of both weight and performance aspects of technology benefits in a single figure of merit, and also enables one to ascertain the benefits of individual technologies even when applied as part of a suite of technologies.

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## Introduction

It is well known that the aerospace industry is more sensitive to vehicle weight as a primary figure of merit for vehicle designs than any other automotive industry. This is because weight (or mass) is a strong driver on vehicle performance and cost, and so takes a central role in the vehicle design process. In fact, vehicle weight is so important that competitive advantage is often sought largely or exclusively on the basis of having a lighter weight than the competitor.

A notable case in point is the Mitsubishi A-6M “zero,” which was the Japanese front-line fighter plane throughout World War II. The A-6M was designed to meet a set of requirements that were far in excess of any Japanese fighter aircraft up to that point in time (Horikoshi, 1970). The specifications decreed that it was to have twice the range of the previous generation fighter, maneuverability comparable to or better than the most maneuverable Japanese fighter at that time, superior climb and acceleration, and a top speed more than 100 mph faster than the fastest Japanese fighter of the day. Moreover, there was not sufficient time to develop a new powerplant, so an up-rated version of an existing engine had to be used.

The design and development of an aircraft to meet these exceedingly challenging expectations required a great deal of innovation, effort, and resolve on the part of the A6M’s chief engineer, Jiro Horikoshi, and his design team. They quickly realized that the key to meeting their goal was to concentrate on two things: aerodynamic cleanliness and ruthless weight control. The latter was especially critical not only because it impacted performance and cost, but because Japan was a resource-limited country that had to import virtually all raw materials, including Aluminum.

In response to this challenge, Dr. Horikoshi instituted extremely strict weight control measures. Project policy was that any design change which might result in a weight savings of 1/30,000 or more of the total airplane weight was to be studied seriously. Weight was tracked so closely that when the first prototype was completed and weighed, there was only 15 pounds difference between actual and estimated weight, and airframe weight growth from design concept to prototype was miniscule. The airplane that emerged was superior to anything in the Pacific theatre at its time of introduction, and one of the finest fighter aircraft of the war.

Though the A6M is somewhat exceptional in regards to the importance of the role played by mass properties engineering, the situation is basically the same for any vehicle design. Vehicle mass is always an important factor because it impacts virtually every aspect of vehicle performance, cost, and size. The only difference between the aerospace industry and any other automotive industry is that vehicle weight has a stronger influence than it does for any other class of vehicle (ship, car, rail, etc.). Consequently, mass properties engineering has evolved into a separate and distinct discipline within aerospace engineering. In fact, aerospace manufacturers typically have entire engineering organizations devoted exclusively to the task of mass properties estimation, tracking, and control.

The fundamental reason that aerospace vehicles are more sensitive to vehicle weight than other modes of automotive motion is that vehicle weight is a strong driver on losses. For aircraft, these losses come in the form of induced drag work due to production of lift required to support the weight of the vehicle in flight. This loss comes not only through the direct mechanism of increased drag work due to lift, but also indirectly through performance requirements. The U-2 is an example of an aircraft wherein weight was strongly driven by performance requirements because every pound of vehicle weight decreased climb ceiling by 1 ft (Rich & Janos, 1994, P. 125). Therefore, an increase in weight must be offset by having a larger wing and engine if climb ceiling is to be maintained. The result is a “snowball” effect where indirect contributors to weight growth are larger than the direct contributors. The relationships between weight and vehicle performance are relatively well known and have been treated analytically (Staton, 1996, P. 3-2).

This work will focus instead on the relationships between *thermodynamic performance* and *weight*. The primary thesis upon which this work is based is the idea that both thermodynamic performance and weight aspects of design can be quantified in terms of gross weight. To understand this, consider performance from a thermodynamic point of view. It is intuitively obvious that the work used for vehicle motion comes from the work potential stored in the fuel. Furthermore, there must be a one-to-one correspondence between fuel weight and total usage of work potential (loss incurred) during the mission. Therefore, *it should be possible to quantify*

losses incurred during the mission (such as drag work, engine inefficiencies, etc.) in terms of the fuel weight required to offset those losses. This is the crux of the method proposed in this paper: to quantify aerothermodynamic aspects of design performance in terms of fuel weight chargeable to each individual source of loss. This approach allows one to make “apples-to-apples” comparisons and trades between weight and performance. The result is effectively a unified weight/performance theory of modern design. This is then applied as a unifying framework to evaluate airframe technology concepts.

E. H. Heinemann once claimed that aircraft manufacturers paid insufficient attention to eliminating useless weight, and that every pound of needless gadgetry contributed ten times its weight to gross weight (Bright, 1978; AW&ST, 30Jun52, P82). The method proposed above would provide a structured and accurate way to calculate Heinemann’s ‘gadget gross weight’ contribution. Moreover, the methods pioneered herein will find good application in the areas of weight planning & control, and “value of a pound” analyses (Staton, 1996).

## Background

The heart of the aircraft design process is making trades between propulsion, aerodynamics, and vehicle mass properties in order to obtain the best possible product. The primary methods used today to make these decisions are analysis and trade studies (Raymer, 1992, Pg 534). Typically, this involves parametric variation of design parameters to observe their impact on overall vehicle weight and performance. This information is then used to make a rational selection as to what combination of design parameters will yield the most desirable compromise between the competing requirements.

However, new ideas in the fields of thermodynamics are making possible alternative ways of formulating design trades that are complimentary to existing methods. The key enabling development is the emerging field of second-law thermodynamic analysis, which deals with estimation and maximization of thermodynamic work potential. This work has culminated in the development of several basic methods for estimation of maximum work available from a thermodynamic system and minimization of associated losses. One of the most prominent is *entropy generation minimization*, or EGM (Bejan, 1996). EGM uses entropy as an index of work loss rather than calculating the work loss directly. Minimization of entropy generation via EGM is equivalent to maximization of work potential, as evidenced by the Gouy-Stodola lost work theorem (Bejan, 1982):

$$W_{lost} = T_0 \Delta S \quad (1)$$

where  $W_{lost}$  is the destruction of work potential,  $T_0$  is ambient (reference) temperature, and  $\Delta S$  is entropy creation. Another well known second law method is *exergy analysis*, which allows the calculation of maximum work that can be extracted from a substance in bringing it into equilibrium with its environment (Li, 1996). Other work FoMs applicable to aerospace vehicle design have also emerged, such as *available energy* (Nichols, 1953), and *thrust work potential* (Riggins, 1997). All of these methods can be used to calculate theoretical work potential inherent to the fuel used to power an aircraft (and loss thereof). They are a critical element needed to make the methods of this paper workable.

The theoretical details regarding the differences between these three work potential figures of merit (FoMs) and their applicability to aerospace vehicle design have been discussed in detail elsewhere (Roth 2000a,b,c). Therefore, this paper will not discuss how to go about calculating thermodynamic work potential of a fuel. Instead, it is taken as axiomatic that it is possible to analytically calculate usage (and loss) of thermodynamic work potential, and it is assumed that work potential usage throughout the vehicle mission is known *a priori*.

A second element that is critical to the development of practical weight/performance methods is the concept of weight chargeability, which is nothing more than a bookkeeping scheme for assigning accountability for empty weight (meaning zero fuel weight) and fuel weight to its underlying source. There is already a well-developed body of work in the field of mass properties engineering that is focused on tracking and assigning accountability for empty weight, based on standardized weight groupings. An example of a typical empty weight grouping scheme is given in SAWE recommended practice 8A (group and detail weight statements).

Brief perusal of this document quickly reveals that zero fuel weight is accounted in great detail, whereas fuel weight is treated as a single lump sum, or at best, broken into trapped, reserve, and mission fuel components.

This situation begs the question: why is it that fuel weight is treated as a lump sum and not broken into its constituent components according to the various loss mechanisms it is used to overcome? It is intuitively obvious that some portion of the fuel used during the mission of an aircraft (or any other vehicle, for that matter) must be attributable to each and every loss and work storage mechanism associated with the aircraft. Why, then, isn't fuel weight ever broken down into its various "chargeable" components? The weight/performance methods developed herein seek to answer the question of how fuel weight chargeability can best be quantified in an analytical way based on the physics of the problem.

Finally, one must have considerable understanding of aerospace vehicle design in order to apply the concepts embodied in this paper. By extension, this requires a good working knowledge in aerodynamics, thermodynamics, weights engineering, propulsion system performance, mission analysis, and general vehicle performance. This discussion assumes that the reader is familiar with these subjects.

## Theory

From a purely abstract point of view, the fundamental problem addressed in this paper is the way in which vehicle mass properties and performance are treated as separate engineering disciplines with little recognition of the thermodynamic relationships that link the two together. It is intuitively obvious that many design decisions have implications on both vehicle weight and performance. These implications must be quantified at the vehicle level and in terms of a common figure of merit that is capable of capturing the essence of both weight and performance aspects of design. Thermodynamic work potential is a FoM suitable to this purpose.

The basic reasoning behind this idea can be explained as follows: it is clear that a finite amount of work is done during the completion of a prescribed vehicle mission. This work is manifested either as a loss or as the transformation of one form of work potential into another. If all the work potential used during the mission comes from mission fuel, then every incremental quantity of fuel contains the same potential for doing work and is independent of the way in which it is used. Given these presuppositions, it is logical to expect that the amount of fuel used to supply work potential to each work "sink" during the vehicle mission is proportional to the total work potential used by that work sink mechanism.

The objective of this section is to derive a mathematical expression for this idea. First, the basic principles and theoretical underpinnings are developed for the restricted case of cruising flight. The usefulness of these theoretical ideas is then illustrated using a simple example problem. Later, the theoretical principles are expanded to include the general case of maneuvering, quasi-steady flight. Again, it is assumed that the work potential usage throughout the mission is known from prior analysis.

### ***Elementary Case: Cruising Flight***

Consider the elementary case of an aircraft in steady cruising flight at constant L/D. Starting with the notion of fuel work potential, it is clear that the work potential initially present in the fuel must either appear as useful thrust work or be destroyed by the engine (assuming that thrust work is the only useful output from the propulsion system). This can be expressed mathematically as a fuel work potential balance:

$$\frac{d(\text{Thrust Work})}{dt} = TV_0 = DV_0 = \frac{d(\text{Fuel Work Potential})}{dt} - \frac{d(\text{Propulsion System Losses})}{dt} \quad (2)$$

where T is net installed thrust, D is total vehicle cruise drag,  $V_0$  is Cruise flight velocity, and t is time. In general, drag work will be composed of many components such as fuselage skin friction drag, wing skin friction drag, wing wave drag, etc. Likewise engine losses are composed of many components such as compressor losses, combustion losses, etc. Assuming there are 'i' components of drag and 'j' components of propulsion system loss, then the above expression can be written:

$$\frac{d(\text{Fuel Work Potential})}{dt} = \sum_i D_i V_0 + \sum_j \frac{d(\text{Propulsion Loss})_j}{dt} \quad (3)$$

---

\* "Sink" meaning a loss (as due to non-isentropic flow processes) or work storage mechanism (i.e., vehicle kinetic or potential energy).

where calculation of the term  $\sum_j \frac{d(\text{Propulsion Loss})_j}{dt}$  is the subject of (Roth, 2000a,b), and calculation of the term  $\sum_i D_i V_0$  is pure aerodynamics. It is obvious based on these equations that:

$$(\text{Loss Fraction due to Drag})_i = \frac{D_i V_0}{\sum_i D_i V_0 + \sum_j \frac{d(\text{Propulsion Loss})_j}{dt}} \quad (4)$$

and

$$(\text{Engine Loss Fraction})_j = \frac{\frac{d(\text{Propulsion Loss})_j}{dt}}{\sum_i D_i V_0 + \sum_j \frac{d(\text{Propulsion Loss})_j}{dt}} \quad (5)$$

Furthermore, if one assumes that all fuel used during the mission has the same work potential then the above equations can be expressed in terms of vehicle fuel fractions:

$$\frac{(\text{Fuel Weight Chargeable to Drag})_i}{(\text{Total Fuel Weight})} = \frac{D_i V_0}{\sum_i D_i V_0 + \sum_j \frac{d(\text{Propulsion Loss})_j}{dt}} \quad (6)$$

and

$$\frac{(\text{Fuel Weight Chargeable to Engine Loss})_j}{(\text{Total Fuel Weight})} = \frac{\frac{d(\text{Propulsion Loss})_j}{dt}}{\sum_i D_i V_0 + \sum_j \frac{d(\text{Propulsion Loss})_j}{dt}} \quad (7)$$

If the propulsion system second law efficiency (or thrust effectiveness) is defined as:

$$\varepsilon_{II} \equiv \frac{TV_0}{(\text{Total Fuel Work Potential})} \quad (8)$$

Then equations 6 and 7 can be summed over i and j, respectively, to yield:

$$\frac{\sum_i (\text{Fuel Weight Chargeable to Drag})_i}{(\text{Total Fuel Weight})} = 1 - \varepsilon_{II} \quad (9)$$

and

$$\frac{\sum_j (\text{Fuel Weight Chargeable to Engine Loss})_j}{(\text{Total Fuel Weight})} = \varepsilon_{II} \quad (10)$$

Note that equations 2-10 implicitly assume that drag work and propulsion system losses are the only work potential “sinks” during cruising flight. In reality, there are other items that require energy derived from fuel work potential including aircraft systems, miscellaneous losses, etc. Obviously, the preceding equations would have to be modified to include additional terms for the more general cruising flight case, but these additional terms are usually small relative to propulsive and aerodynamic losses.

It is easy to check the validity of these simple derivations by examining the extreme cases. In the limit as aerodynamic losses approach zero (as in the case of slow-moving ground vehicles), equations 6 and 7 reduce to:

$$\dot{m}_{f,i} \propto Loss_i \Rightarrow \frac{\dot{m}_{f,i}}{\dot{m}_f} = \frac{(Prop. Loss)_i}{(Total Prop. Loss)} \quad (11)$$

where  $\dot{m}_{f,i}$  is the fuel flow rate chargeable to loss 'i.' And if there were aerodynamic drag, but the propulsion system were perfect (zero loss), equations 6 and 7 would reduce to:

$$\dot{m}_{f,i} \propto D_i \Rightarrow \frac{\dot{m}_{f,i}}{\dot{m}_f} = \frac{D_i}{D} \quad (12)$$

Thus, in steady cruising flight, the fraction of fuel weight chargeable to the drag of a component is simply proportional to the fraction of total drag produced by that component in cruising flight if there are no propulsive losses. If there are propulsive losses but no drag, then fuel weight is chargeable in proportion to the propulsion system loss fraction. These equations are key to enabling *analytical* estimation of chargeable fuel weight.

As an example to illustrate the basic concept, consider the simplest possible case of an aircraft in cruising flight. Suppose that the aircraft has a perfect (no loss) propulsion system and that the weight and drag breakdown for this aircraft in cruising flight is as given in Table 1. The vehicle mission consists of pure cruising flight until all fuel is consumed (no takeoff, landing, climb, etc.). Using the fuel weight-drag proportionality rule of equation 12, it is possible to calculate the fuel weight contribution due to drag chargeability of each component, as shown at left of Table 2, where  $W_F$  is total mission fuel weight. Component empty weight is then added to chargeable fuel weight, with the result shown to the right of Table 2.

**Table 1: Example Assumptions for Weight and Drag Breakdown in Cruising Flight.**

<u>Component</u>	<u>Weight</u>	<u>Drag @ Cruise</u>
Payload	100 lb	---
Fuselage	300 lb	50 ct
Wing	300 lb	50 ct
Tails	100 lb	30 ct
Nacelles	200 lb	20 ct
Fuel	1,000 lb	---
Gross	2,000 lb	150 ct

**Table 2: Component Fuel Weight Chargeability.**

<u>Component</u>	<u>Chargeability</u>		<u>Component</u>	<u>Chargeability</u>
Fuselage	50ct/150ct = 33% $W_F$ = 333 lb		Payload	100 lb
Wing	50ct/150ct = 33% $W_F$ = 333 lb		Fuselage	300+333 = 633 lb
Tails	30ct/150ct = 20% $W_F$ = 200 lb		Wing	300+333 = 633 lb
Nacelles	20ct/150ct = 13% $W_F$ = 130 lb		Tails	100+200 = 300 lb
	1,000 lb		Nacelles	200+130 = 333 lb
			Empty weight	
			Fuel burned to overcome drag	

**Table 3: Revised and Final Component Chargeable Weight Breakdowns.**



<b><i>Component</i></b>	<b><i>Weight</i></b>	<b><i>Weight</i></b>		<b><i>Component</i></b>	<b><i>Weight</i></b>	<b><i>Weight</i></b>
Payload	0.1(333) =	33 lb		Payload	100+33 =	133 lb
Fuselage	0.3(333) =	100 lb		Fuselage	633+100 =	733 lb
Wing	0.3(333) =	100 lb		Wing	300+100 =	400 lb
Tails	0.1(333) =	33 lb		Tails	300+33 =	333 lb
Nacelles	0.2(333) =	67 lb		Nacelles	333+67 =	400 lb
<b>Fuel Required to Overcome Component Weight</b>				<b>Total Component-wise Weight Chargeability</b>		

Note that the total wing chargeable fuel weight due to drag is 333 lb. However, the function of the wing is to support vehicle weight. Therefore, one can argue that wing drag (and chargeable fuel weight) is due to the weight of each component. Consequently, it makes sense to distribute wing chargeable fuel weight amongst the various components in proportion to the empty weight fraction of each, as shown to the left of Table 3. The “empty weight corrected” vehicle chargeable weight stack up is given on the right side of Table 3.

This scheme effectively penalizes each component not only for its contribution to empty weight, but also for its *incremental contribution to fuel weight*. In this example, it is clear that since the fuselage is heavy and produces non-productive drag, it receives the bulk of the gross weight chargeability. Also, the tail and nacelle chargeable weights are a staggering 333% and 200% of their empty weights, respectively.

### ***The General Case***

Next, the more general case of quasi-steady maneuvering flight is presented as a series of scenarios starting with a simple model and progressing towards the general model for vehicular motion. The simplest model for vehicular motion is a rocket in free space that must undergo a specified  $\Delta V$ . The work potential balance equation for this situation is:

$$(\text{Fuel Work Potential}) = m \frac{\Delta V^2}{2} \quad (13)$$

where  $m$  is vehicle mass, and  $\Delta V$  is change in vehicle velocity. Therefore, the fuel fraction chargeable to acceleration is:

$$\frac{(\text{Fuel Chargeable to Acceleration})}{(\text{Total Fuel})} = \frac{m \frac{\Delta V^2}{2}}{(\text{Fuel Work Potential})} = 1 \quad (14)$$

Therefore, all fuel weight for this case is chargeable to vehicle acceleration. If this same rocket is also moving through a gravity field, then the work balance equation becomes:

$$(\text{Fuel Work Potential}) = m \left( \frac{\Delta V^2}{2} + g\Delta h \right) \quad (15)$$

where  $g$  is gravitational acceleration, and  $\Delta h$  is change in altitude. Fuel weight chargeability for this case is:<sup>†</sup>

$$\frac{(\text{Fuel Chargeable to Acceleration})}{(\text{Total Fuel})} = \frac{m \frac{\Delta V^2}{2}}{(\text{Fuel Work Potential})} = \frac{m \frac{\Delta V^2}{2}}{m \left( \frac{\Delta V^2}{2} + g\Delta h \right)} \quad (16)$$

<sup>†</sup> Incidentally, it is these two terms that make weight such an all-important driver on launch vehicle design, as launch necessarily requires that a large  $\Delta V$  and  $\Delta h$  be imparted to the vehicle and its cargo.

$$\frac{(\text{Fuel Chargeable to Climb})}{(\text{Total Fuel})} = \frac{mg\Delta h}{(\text{Fuel Work Potential})} = \frac{mg\Delta h}{m\left(\frac{\Delta V^2}{2} + g\Delta h\right)} \quad (17)$$

Finally, if aerodynamic and propulsive losses are included, the work potential balance equation becomes:

$$(\text{Fuel Work Potential}) = m\left(\frac{\Delta V^2}{2} + g\Delta h\right) + \sum_i D_i V_o + \sum_j (\text{Prop. Loss})_j \quad (18)$$

and partitioning of fuel weight chargeability becomes:

$$\frac{(\text{Fuel Chargeable to Accel.})}{(\text{Total Fuel})} = \frac{m\frac{\Delta V^2}{2}}{(\text{Fuel Work Potential})} = \frac{m\frac{\Delta V^2}{2}}{m\left(\frac{\Delta V^2}{2} + g\Delta h\right) + \sum_i D_i V_o + \sum_j (\text{Prop. Loss})_j} \quad (19)$$

$$\frac{(\text{Fuel Chargeable to Climb})}{(\text{Total Fuel})} = \frac{mg\Delta h}{(\text{Fuel Work Potential})} = \frac{mg\Delta h}{m\left(\frac{\Delta V^2}{2} + g\Delta h\right) + \sum_i D_i V_o + \sum_j (\text{Prop. Loss})_j} \quad (20)$$

$$\frac{(\text{Fuel Chargeable to Prop.})_j}{(\text{Total Fuel})} = \frac{(\text{Prop. Loss})_j}{(\text{Fuel Work Potential})} = \frac{(\text{Prop. Loss})_j}{m\left(\frac{\Delta V^2}{2} + g\Delta h\right) + \sum_i D_i V_o + \sum_j (\text{Prop. Loss})_j} \quad (21)$$

$$\frac{(\text{Fuel Chargeable to Drag})_i}{(\text{Total Fuel})} = \frac{D_i V_o}{(\text{Fuel Work Potential})} = \frac{D_i V_o}{m\left(\frac{\Delta V^2}{2} + g\Delta h\right) + \sum_i D_i V_o + \sum_j (\text{Prop. Loss})_j} \quad (22)$$

Given a viable means of obtaining an internal loss stack-up, as well as workable drag and weight chargeability models, it is possible to calculate the total loss attributable to each functional component with the aid of the above equations. However, in order to do this, it is necessary to have detailed knowledge of the drag split at each instant in flight, as well as detailed knowledge of the engine internal loss mechanisms. Moreover, the portion of thrust used for climb and acceleration must be known at all times.

For the general case of maneuvering flight, it is necessary to develop a differential expression relating the instantaneous fuel flow rates,  $\dot{m}_{f,i}$ , to each term of energy loss and storage in the work potential balance equation. This implies that it is necessary to either modify a mission analysis code to give these outputs in integrated form, or utilize the mission analysis data output from an existing code and post-process it to obtain the relevant loss data. The latter is the approach used in this work, and is based on piecewise integration of mission time history data from the FLOPS mission analysis code (McCullers, 1998). The basic data required for this task is knowledge of flight condition, vehicle weight, and propulsion system throttle setting at every time step throughout the mission.

## Loss Management Methodology

The theoretical ideas developed in the previous section are the raw tools needed to construct a comprehensive “loss management” model for thermodynamic work potential. However, in order to be useful, these ideas must be integrated into an overarching method if they are to be used effectively for vehicle design. The method developed for this purpose is shown in Figure 1, and is divided into two regions labeled “performance engineering methods” and “weights engineering methods.” The objective is to unify these two separate

disciplines into a single framework by quantifying thermodynamic performance aspects of design in terms of gross weight fractions.

First, consider the right side of this figure, which shows the typical sequence of activities associated with mass properties engineering today. Given a basic configuration, the vehicle is decomposed into its functional components (at the preliminary design level) or into individual parts (at the detail design level). Standard mass properties estimation methods are then used to obtain a weight estimate for each component or part, and these are subsequently “rolled up” into a vehicle empty weight statement. The next step is to assign weight chargeability to each functional component. In fact, the weight statement arrived at in the previous step implies chargeability because vehicle empty weight is usually partitioned according to functional group.

Next, consider the steps shown in the left side of the figure, under the heading “performance engineering methods.” Steps 1-4 constitute the heart of the loss management method proposed herein. Their purpose is to develop a detailed model for usage of thermodynamic work potential throughout the vehicle mission, as described in Roth (2000d). The result from steps 1-4 is a partitioning of the total work potential consumed through the mission of the vehicle. The purpose of steps 5-7 is to transform the thermodynamic work potential results from the first four steps into chargeable fuel weight, and ultimately into operating costs (steps 5-7).

When the results from mass properties and aero-thermodynamic performance engineering are combined, the result is a detailed accounting of fuel weight chargeability and empty weight chargeability that yields explicit knowledge of the empty weight and fuel weight contribution of each functional group. This information can then be used in conjunction with cost accounting and activity-based costing methods to arrive at a per-trip operating cost breakdown, and ultimately, estimation of total LCC attributable to each loss mechanism.

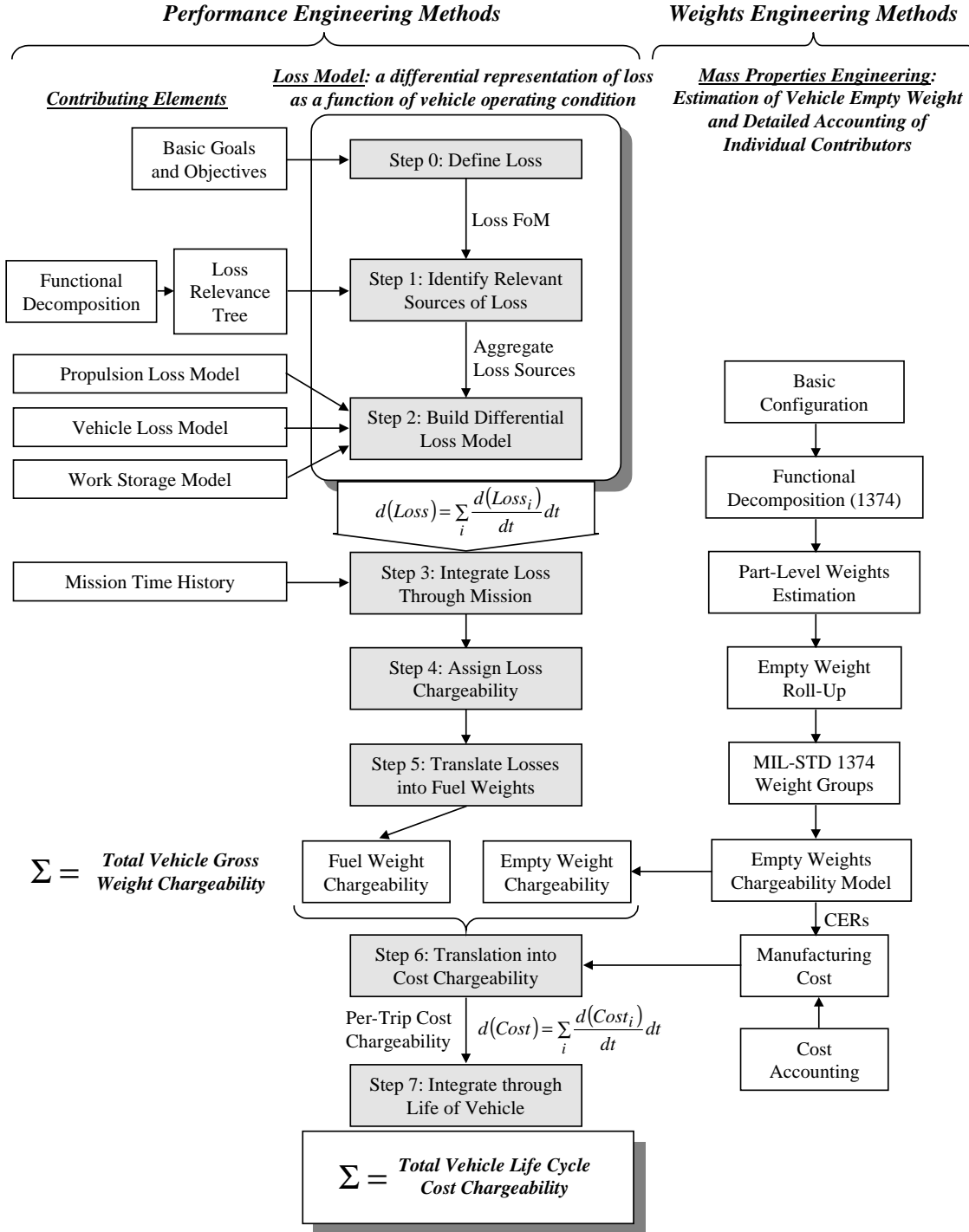
The focus of this paper is on development of steps 5-7 since they are the bridge linking vehicle thermodynamic performance to mass properties. As this paper will demonstrate, once usage of thermodynamic work potential is known, it is a straightforward exercise to determine gross weight chargeability and operating cost chargeability. Ultimately, the result from application of this method is detailed knowledge regarding the sum total cost attributable to each and every loss associated with operation of the vehicle over its useful life.

### ***Determination of Empty Weight Chargeability***

The concept of weight chargeability is a notion that has been used by the aerospace industry for many years, though it is not referred to by that name. The truth of this statement is nicely illustrated in a comment made by Larry Bell regarding the P-39 “Airacobra.” Recall that the P-39 had a unique arrangement in which the engine was located aft of the cabin (amidships) and powered the propeller via a 10 ft extension shaft running between the pilot’s legs. This arrangement required exceptional fuselage bending stiffness to maintain shaft alignment, and when asked how much these stiffness requirements added to fuselage weight (fuselage weight *chargeable* to the propulsion system), Bell claimed that the answer was ~100 lbs (Mathews, 1996). Though the truth of this statement is subjective due to its dependence on assumptions, the notion that weight penalties associated with the mid-engine arrangement can be quantified in terms of chargeable fuselage weight is beyond question.

The implication of the previous statement is that non-fuel vehicle weight can be partitioned into chargeable groups in a manner that reflects the fundamental mechanisms driving them. This process of allotting portions of airframe weight to various functional components is defined here as *weight chargeability*. The logical approach to assigning weight chargeability is to use established industry standard weights specifications such as MIL-STD-1374A (which defines standard weights groups applicable to all aircraft) as a framework for establishing weight chargeability of the various airframe subsystems. If this approach is used, it should be possible to assign weight chargeability on a relatively straightforward basis.

The difficulty in assigning weight chargeability arises when it is necessary to account for interactions between functional groups. For instance, added wing structural weight required to support pylon and engine loads is chargeable to the propulsion system. All such interactions must be *explicitly* accounted for if their effect on the aircraft is to be captured, and it is up to the analyst to recognize and account for these effects when appropriate. Nevertheless, the presence of these interactions should not be an obstacle to the creation of meaningful empty weight chargeability schemes.



**Figure 1: Analysis Methodology for Estimation of Chargeable Gross Weight.**

#### **Steps 0-4: Determine Chargeability of Thermodynamic Work Potential**

The general methodology for determination of thermodynamic work potential chargeability is divided into four basic steps, as shown in the flowchart of Figure 1. In brief, step “0” in the construction of a loss management model is to explicitly define loss in a way most suited to the needs of the current analysis. It was previously mentioned that there are a variety of ways to measure thermodynamic loss, and the choice of which to use depends on the situation at hand. When this is known and clearly understood, the first step is to clearly identify all loss

mechanisms that are significant to the operation of the vehicle. The ultimate outcome is a detailed listing of all sources of loss incurred by the vehicle during the course of a mission.

Next, a mathematical representation of each loss source is created in step two, which necessarily requires extensive information on propulsion system and vehicle systems performance. The result of steps 0-2 is a differential loss model that describes the instantaneous loss breakdown of the vehicle as a function of operating condition. The construction of an accurate and complete differential representation of loss is an essential feature that enables the creation of vehicle loss management models.

Step three is to integrate this differential loss model through time over a single vehicle mission or duty cycle to obtain total loss chargeable to each loss mechanism. Obviously, it is imperative to use a vehicle mission which is representative of the operation that the vehicle will actually experience in service. Finally, one must assign chargeability for each loss to its underlying source. The objective of step four is to allocate each loss to the factor(s) that drive it such that the true thermodynamic cost of each design decision can be understood.

### **Step 5: Transformation of Thermodynamic Losses into Fuel Flow Chargeability**

The ultimate objective of this paper is to devise a method for quantifying losses in terms of fuel weight consumed during the mission such that the impact of thermodynamic loss can be expressed in terms of an airframe-level parameter, namely fuel weight. Therefore, the focus here is on completing the bridge linking work and loss to fuel weight. This is done through a formal development of the equations linking the two and the resulting transformation is shown to be intuitively appealing.

For each loss figure of merit discussed by Roth (2000d), one can calculate a maximum work theoretically available per unit air flow through the engine, as given by the sum of the losses and useful work output:

$$w_{\text{ideal}} = w_{\text{out}} + \sum \text{Losses} \quad (23)$$

where:  $w_{\text{ideal}}$  is the maximum theoretical work (or power) output per unit mass, and  $w_{\text{out}}$  is the actual work (or power) output per unit mass. If this ideal work output per unit air flow rate is divided by the fuel to air ratio, the result is *ideal useful work per pound of fuel* (denoted henceforth as  $W_{f,\text{ideal}}$ ):

$$W_{f,\text{ideal}} = \frac{W_{\text{ideal}}}{f/a} \quad (24)$$

It should be noted that the value obtained for  $W_{f,\text{ideal}}$  differs considerably between the various work loss figures of merit, which explains why it is important to establish guidelines as to which is the correct loss figure of merit for a particular application. The fundamental idea is that just as fuel has an ideal heating value per unit mass, it also has an ideal work potential per unit mass. This ideal work per unit mass of fuel is the bridge linking work and loss to fuel weight. To calculate the fuel flow rate chargeable to a particular loss mechanism (indexed as  $i$ ):

$$(\text{Fuel Flow})_i = \frac{(\text{Power Loss})_i}{W_{f,\text{ideal}}} (\text{Fuel Flow})_{\text{total}} \quad (25)$$

If this fuel flow chargeability is integrated through the mission, the result is the total fuel weight chargeable to loss mechanism  $i$ :

$$(\text{Fuel Weight})_i = \int_{\text{takeoff}}^{\text{landing}} (\text{Fuel Flow})_i dt \quad (26)$$

It follows that the sum of the loss mechanisms must be equal to the total fuel flow rate:

$$(\text{Total Mission Fuel}) = \sum_i (\text{Fuel Weight})_i \quad (27)$$

This description of fuel flow chargeability relative to work and loss fits naturally with one's intuitive expectation that the fuel flow chargeability of a particular loss should be proportional to its fraction of the ideal work potential available in the fuel according to the proportionality rule:

$$\frac{(\text{Fuel Flow})_i}{(\text{Fuel Flow})_{\text{total}}} = \frac{(\text{Loss})_i}{(\text{Ideal Work Potential})} \quad (28)$$

### **Step 6: Translation into Cost Chargeability**

Up to this point, the focus has been exclusively on weight and thermodynamic performance. However, the aerospace industry today is being driven not by performance, but by cost. In particular, operating cost and acquisition cost are major factors that influence product acceptance, so the industry as a whole has a keen interest in understanding and tracking costs, usually through elaborate cost accounting systems.

In general, these cost accounting systems allow aerospace manufacturers to quantify exactly how much each part and manufacturing process adds to the total cost of the aircraft. Likewise, operating cost accounting schemes are quite elaborate and allow operators to track each individual contributor to cost in great detail, with one exception: fuel cost. Fuel cost constitutes roughly 25% of total aircraft operating costs, and there are many factors that contribute to fuel cost (vehicle weight, drag, engine efficiency, etc.). However, the individual contributors that make up total fuel cost are usually not known. For instance, most operating cost models cannot estimate how much additional fuel is burned due to compressor losses, or due to induced drag, etc. Consequently, most operations cost models either estimate chargeable fuel cost via sensitivity methods (General Electric, 1993), or they make assumptions based on experience as to what the most reasonable fuel cost split should be. An example of the latter approach was given by Hauser (1999), wherein his objective is to estimate the propulsion system's total contribution to vehicle fuel burn. He does this by assuming that 50% of the fuel burn is engine-related fuel cost, the remainder being airframe-related.

However, the previous section showed that thermodynamic work potential can be quantified in terms of fuel weight fractions. Once this is done, it is an obvious extension to convert fuel weight fractions into fuel cost fractions chargeable to each source of loss. Since fuel price is typically proportional to fuel weight, the cost chargeable to each loss incurred over the vehicle mission is simply proportional to the chargeable fuel weight attributed to each loss. Therefore, loss management methods provide a direct analytical means of calculating propulsion system contribution to fuel cost (or any other contribution, for that matter). The mathematical expression of this idea is nearly trivial:

$$\left( \text{Fuel Cost} / \text{Trip} \right)_i = \left( \text{Fuel Burn} / \text{Trip} \right)_i * (\text{Fuel Cost}) / \text{lb} \quad (29)$$

where 'i' is an index over all components of chargeable fuel burn calculated in step 5.

### **Step 7: Integrate Through Life of Vehicle**

Given an analytical breakdown of per-trip fuel cost, the final step in the analytical process is to integrate these costs through the life of the vehicle to obtain an estimate of the total cost incurred by each loss mechanism present during vehicle operation. This is merely a matter of accumulating totals for the chargeable fuel cost per mission times the number of missions flown through the life of the vehicle. Expressed mathematically:

$$(\text{Loss LCC})_i = \sum_i \left( \text{Fuel Cost} / \text{Trip} \right)_i * (\text{Number of Missions}) \quad (30)$$

Obviously, if the true life cycle cost of each loss mechanism is to be accurately known, one would have to make an adjustment for cost escalation over time, but this is a well known accounting procedure and will not be discussed here. The reader is instead referred to Fabrycky & Blanchard (1991) or a similar text for such details.

## Application to the F-5E

The application used to demonstrate and validate the methods developed in this paper is the Northrop F-5E “Tiger II” fighter aircraft. The F-5E was selected as a validation case because of its supersonic performance, and because it is a known quantity with well-established aerodynamic and propulsion performance properties. The primary mission for the Northrop F-5E is a subsonic area intercept of 225 nmi combat radius and a combat load consisting of 4,400 lb fuel, two wingtip-mounted AIM-9J missiles and ammunition for internal guns. The design mission has a TOGW of 15,633 lb and an empty weight of 10,463 lb. The mission profile, assumptions, and allowances are shown in Figure 2. The mission definition includes allowances for 1 minute at maximum afterburner (A/B), and 2 minutes at full military power for initial climb. After this, the climb schedule is assumed to be that for minimum fuel to climb, followed by cruise at the altitude and Mach number for best specific range (denoted BCA/M). The combat segment consists of a military power climb to 50,000 ft, followed by 5 minutes at maximum afterburner. It is assumed that only the weight of the missiles is jettisoned during combat, while the entire ammunition load is retained. Cruise back to base is BCA/M, and no range or time credit is given for final descent. Allowance is made for a 20 minute loiter and 5% fuel reserve. In addition, a 5% fuel flow conservancy is assumed throughout the mission, meaning all fuel flows are augmented by 5% to allow a margin of error. The mission and assumptions used herein are taken from the manufacturer’s published performance estimates given standard aircraft characteristics charts (Northrop, 1976), and are representative of typical mission rules and assumptions commensurate with current industrial practice.

### Steps 0-4: Determine Chargeability of Thermodynamic Work Potential

The work potential figure of merit chosen for demonstration on the F-5E example is thrust work potential,  $W_p$ . It is defined as the thrust work that would be obtained in expanding a flow at a given temperature and pressure to ambient pressure such that the thrust work obtained is equal to the thrust produced times the flight velocity of the aircraft (Riggins, 1997). This can be normalized by airflow rate to give specific thrust work potential:

$$W_p \equiv \frac{Sa(u)}{J} \quad (31)$$

where  $Sa$  is stream thrust,  $u$  is flight velocity, and  $J$  is the heat-work conversion constant. Thrust work potential is uniquely suited as a work potential FoM for jet-propelled aircraft because it is truly a measure of the *ideal thrust work* available from a given flow and it is loss in the potential to produce thrust work that is relevant to the design of jet engines. Riggins (1997) has pointed out that optimization of stream thrust and thrust work potential at the component level will lead to maximum thrust (and thrust work) propulsion systems. Also, it should be noted that thrust work potential is a special case of available energy, and by extension, a special case of exergy, as discussed by Roth (2000b,c).

Since the focus of this analysis is on quantification of thermodynamic performance in terms of weight, the breakdown of work potential usage for the F-5E subsonic area intercept mission is taken as a given. This has already been calculated for the F-5E subsonic area intercept mission by Roth (2000d), and is shown in the left-most column of Table 4. Note that this table breaks vehicle losses into three broad categories: propulsive losses, aerodynamic losses, and mass properties losses. Propulsive losses were calculated using a cycle model

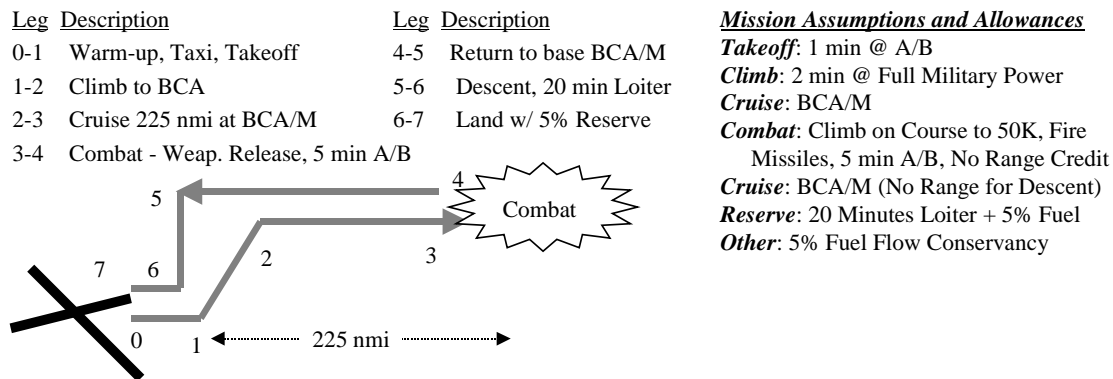


Figure 2: F-5E Subsonic Area Intercept Mission Profile.

for the J85-GE-21 installed engine, and aerodynamic losses were calculated based on the known drag breakdown for the F-5E. The mass properties losses were calculated by assuming that the induced drag is directly chargeable to the weight of the vehicle, and therefore the “thermodynamic cost” of vehicle weight is manifested as induced drag work. Aerodynamic drag losses and vehicle weight losses are further partitioned according to functional component, these being grouped into fuselage, wing, horizontal tail, vertical tail, and stores. It should be noted that this partitioning scheme is arbitrary and is only one of many valid bookkeeping schemes that could have been employed. The choice as to which partitioning scheme is most appropriate is dependent on the circumstances of the problem at hand and the intent of the analyst.

**Table 4: Chargeability of Thermodynamic Work Potential, Fuel Weight, and Fuel Cost for the F-5E Subsonic Area Intercept Mission.**

Component of Work Usage		Thermodynamic Work Potential		Chargeable Fuel Weight		Chargeable Fuel Cost	
		Thrust Work Potential	Thrust WP Usage	Chargeable Fuel Weight	Chargeable Fuel Weight	Fuel Cost (\$ @ \$0.7/gal)	Thrust Work Pot. Cost (%)
		(HP-min)	(% Total)	(lbm)	(% Total)		
<b>Propulsion System</b>							
Component Losses	Afterbody Drag	1,997	0.7%	28.8	0.7%	3.05	0.7%
	Inlet Spillage Drag	3,969	1.3%	57.2	1.3%	6.07	1.3%
	Nozzle Internal Aerodynamic Losses	5,387	1.8%	77.6	1.8%	8.23	1.8%
	Afterburner Combustion Inefficiency	11,970	3.9%	172.5	3.9%	18.30	3.9%
	Tailpipe Pressure Drop	4,746	1.6%	68.4	1.6%	7.25	1.6%
	Turbine Losses	17,124	5.6%	246.8	5.6%	26.18	5.6%
	Turbine Cooling	16,174	5.3%	233.1	5.3%	24.72	5.3%
	Accessories PTO and Bearing Losses	2,101	0.7%	30.3	0.7%	3.21	0.7%
	Combustion Inefficiency	6,209	2.0%	89.5	2.0%	9.49	2.0%
	Combustor Pressure Drop	6,524	2.1%	94.0	2.1%	9.97	2.1%
	Compressor Losses	27,111	8.9%	390.7	8.9%	41.44	8.9%
	Inlet Pressure Recovery	10,450	3.4%	150.6	3.4%	15.97	3.4%
Total Engine Component Losses		Σ= 113,762	37.3%	1,639.6	37.3%	173.90	37.3%
Total Propulsion System Losses		113,762	37.3%	1,639.6	37.3%	173.90	37.3%
Thrust Work		191,529	62.7%	2,760.4	62.7%	292.77	62.7%
<b>Aerodynamic Drag Work</b>							
Wave Drag	Fuselage Wave Drag	17,226	5.6%	248.3	5.6%	26.33	5.6%
	Wing Wave Drag	3,852	1.3%	55.5	1.3%	5.89	1.3%
	Horizontal Tail Wave Drag	901	0.3%	13.0	0.3%	1.38	0.3%
	Vertical Tail Wave Drag	682	0.2%	9.8	0.2%	1.04	0.2%
Total Wave Drag Work		Σ= 22,661	7.4%	326.6	7.4%	34.64	7.4%
Skin Friction	Fuselage Skin Friction	37,925	12.4%	546.6	12.4%	57.97	12.4%
	Wing Skin Friction	28,652	9.4%	412.9	9.4%	43.80	9.4%
	Horizontal Tail Skin Friction	9,268	3.0%	133.6	3.0%	14.17	3.0%
	Vertical Tail Skin Friction	8,417	2.8%	121.3	2.8%	12.87	2.8%
Total Skin Friction Drag Work		Σ= 84,262	27.6%	1,214.4	27.6%	128.80	27.6%
Stores Drag		5,446	1.8%	78.5	1.8%	8.32	1.8%
Induced Drag Work		74,267	24.3%	1,070.4	24.3%	113.53	24.3%
Total Drag Work		186,636	61.1%	2,689.9	61.1%	285.29	61.1%
Mass Properties	Induced Drag Work Due to Vehicle Weight	74,267	24.3%	1,070.4	24.3%	113.53	24.3%
	Work Due to Structure Weight	26,052	8.5%	375.5	8.5%	39.82	8.5%
	Work Due to Propulsion Weight	9,116	3.0%	131.4	3.0%	13.93	3.0%
	Work Due to Fixed Equip. Weight	9,572	3.1%	138.0	3.1%	14.63	3.1%
	Work Due to Stores Weight	3,466	1.1%	50.0	1.1%	5.30	1.1%
	Work Due to Fuel + Misc. Weight	26,061	8.5%	375.6	8.5%	39.84	8.5%
Total Loss in All Vehicle Systems & Subsystems		305,291	100.0%	4,400.0	100.0%	466.67	100.0%
Net Work Stored in Vehicle Potential Energy		0		0.0		0.00	
Net Work Stored in Vehicle Kinetic Energy		0		0.0		0.00	



It is interesting to note that this work potential chargeability scheme for the F-5E subsonic area intercept mission results in 37.3% of the total usage in work potential being charged to the propulsion system, 36.8% charged to aerodynamic drag work, and 24.3% charged to vehicle weight. The relative parity between these three factors is intuitively appealing in light of the fact that the best vehicle design is inherently a balance between these three factors. Closer examination of the relative percentages in the second column shows that the most significant contributors to loss of thrust work potential in the propulsion system are compressor, turbine, and afterburner losses. Of the aerodynamic losses, skin friction drag is the largest followed by induced drag and wave drag losses. Finally, the induced drag losses are partitioned amongst the various functional groups in proportion to the empty weight of each group.

#### **Step 5: Transformation of Thermodynamic Losses into Fuel Flow Chargeability**

The next step in the analysis process is to convert thermodynamic work potential into chargeable fuel weight using equation 28. The results from this process for the thrust work potential analysis is shown in the center pair of columns in Table 4. Note that the relative percentages for fuel weight chargeability are identical to those shown for thermodynamic work potential. Therefore, 61.1% of the thrust work theoretically available from the J85 cycle is actually converted to thrust work. Of this, approximately 24.3% is converted into induced drag work, with the remainder being chargeable to zero-lift drag. Consequently, 37.3% of the mission fuel weight is charged to propulsion system losses, 24.3% to induced drag, and 36.8% to zero-lift drag.

At this point, fuel weight chargeability can be re-integrated with the vehicle zero fuel weight to determine gross weight chargeability. An example of this process is given in Table 5 for gross weight chargeability as measured using the thrust work potential FoM. From left to right, this table shows the vehicle empty weight, the induced drag (lift) contribution to gross weight, the drag contribution, the propulsive contribution, and finally the total gross weight chargeable to each functional group. Note that the airframe itself is chargeable for 49% of vehicle gross weight, the engines are chargeable for 24% of gross weight, and vehicle systems are chargeable for 18% of vehicle gross weight. The remaining 9% of vehicle gross weight is chargeable to the useful load. These results are also depicted in Figure 3, which contrasts the standard F-5E gross weight breakdown against the chargeable gross weight breakdown. The primary difference between the two is that mission fuel (hatched area) is treated as a lump sum in on the left whereas it is divided amongst the functional components on the right.

The result of this analysis is a detailed picture of how each functional group actually contributes to vehicle size and weight (and cost). The ability to calculate chargeable gross weight is a new and unique capability that has never before been applied to the vehicle design process in a comprehensive and methodical way. Although this example is for the work potential FoM, the same principle applies for exergy or available energy FoMs.

#### **Steps 6 & 7: Integration of Cost Chargeability Through Life of Vehicle**

Once fuel weight chargeability for the F-5E design mission is known, it is a trivial matter to convert chargeable fuel weight into chargeable fuel cost. This idea is suggested in the rightmost pair of columns in Table 4, which shows the breakdown of chargeable fuel cost for the F-5E subsonic area intercept mission, assuming an average fuel cost of \$0.70/gallon. Note closely what the results of this table imply. *Application of this method has provided a means for calculating the fuel cost associated with each and every loss occurring over the mission elapsed time.* For instance, the fuel cost due to compressor inefficiencies was *analytically estimated* to be \$41.44 per mission. The fuel cost due to horizontal tail skin friction drag is \$15.55 per mission. The weight of vehicle fixed equipment costs \$14.63 in fuel per mission, and so on. This is unique information that is not ordinarily available through conventional analysis techniques such as cycle analysis, mission analysis, and vehicle operating cost analysis. Moreover, it is information that is potentially very valuable in weighing the relative merits of design options on an “apples to apples” basis. In effect, the relative cost (or weight) of any design option impacting the propulsive, aerodynamic, or mass properties of the vehicle can be compared directly in terms of cost or weight.

Recall that the previous discussion pointed out shortcomings of current methods with regards to means for estimating fuel flow chargeability. Specifically, the earlier discussion referenced a study by Hauser (1999), in which the objective was to determine the propulsion system contribution to total fuel cost. The results presented in Table 4 are a direct calculation of propulsion system contribution to fuel cost. The results indicate that propulsion-chargeable fuel cost for the F-5E subsonic area intercept mission is 37.3% of total fuel cost.

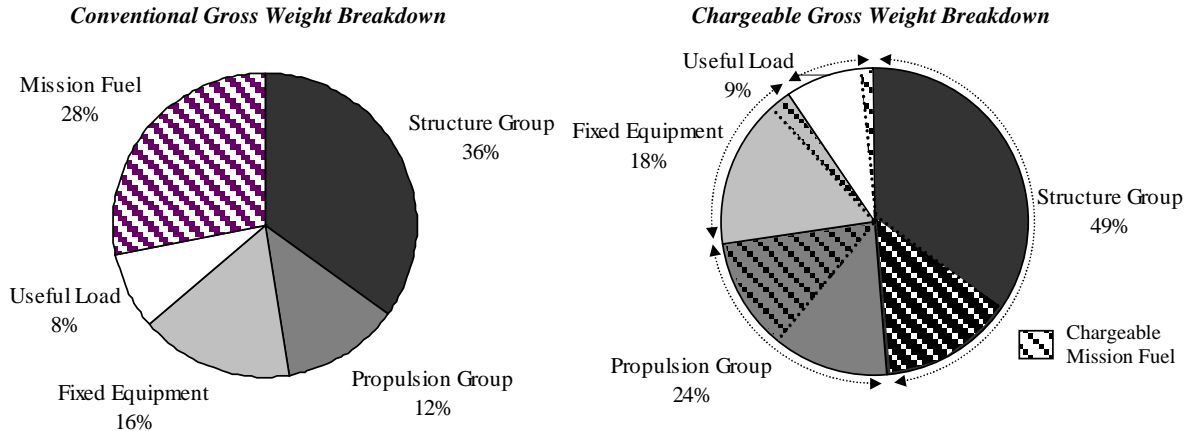
**Table 5: Assembly of Empty Weight and Fuel Weight Chargeability into Gross Weight Chargeability for the F-5E (for the Thrust Work Potential FoM).**

<i>Weight Group</i>	<i>Empty Wt. (lb)</i>	<i>Fuel Ch. Due to Lift (lb)*</i>	<i>Fuel Ch. Due to Drag (lb)**</i>	<i>Fuel Ch. Due to Prop. Loss (lb)</i>	<i>Ch. Gross Weight (lb)***</i>	<i>Ch. Gross Wt. Fraction (%)</i>
<b>Structure Group</b>	5,484.0	531.0	1,564.8	-	7,579.8	0.485
Wing Group	1,315.0	127.3	478.4	-	1,920.7	0.123
Tail Group- Horizontal	155.0	15.0	147.5	-	317.5	0.020
- Vertical	151.0	14.6	134.1	-	299.7	0.019
Body Group	2,648.0	256.4	804.8	-	3,709.2	0.237
Alighting Gear Group -Main	765.0	74.1	-	-	839.1	0.054
-Nose	-	-	-	-	-	-
-Arrest	-	-	-	-	-	-
Engine Section or Nacelle Group	450.0	43.6	-	-	493.6	0.032
Air Induction System	-	-	-	-	-	-
<b>Propulsion Group</b>	1,922.0	186.1	-	1,667.7	3,775.8	0.242
Engine (As Installed)	1,324.0	128.2	-	1,667.7	3,119.9	0.200
Gear Boxes and Drives	206.0	19.9	-	-	225.9	0.014
Exhaust System	-	-	-	-	-	-
Cooling and Drain Provisions	-	-	-	-	-	-
Engine Controls	-	-	-	-	-	-
Starting System	-	-	-	-	-	-
Fuel System	392.0	38.0	-	-	430.0	0.028
<b>Fixed Equipment</b>	2,555.0	247.4	-	-	2,802.4	0.179
Flight Controls Group	427.0	41.3	-	-	468.3	0.030
Auxiliary Power Plant Group	-	-	-	-	-	-
Instrument Group	155.0	15.0	-	-	170.0	0.011
Hyd. and Pneumatic Group	153.0	14.8	-	-	167.8	0.011
Electrical Group	303.0	29.3	-	-	332.3	0.021
Avionics Group	172.0	16.7	-	-	188.7	0.012
Armament Group	869.0	84.1	-	-	953.1	0.061
Furnishings Group	243.0	23.5	-	-	266.5	0.017
Air Conditioning Group	148.0	14.3	-	-	162.3	0.010
Handling Group	85.0	8.2	-	-	93.2	0.006
<b>TOTAL WEIGHT EMPTY</b>	9,961.0	964.4	-	-	10,925.4	0.906
Crew	240.0	23.2	-	-	263.2	0.017
Fuel - Unusable	140.0	13.6	-	-	153.6	0.010
Fuel - Usable	4,400.0	-	-	-	-	-
Oil - Engine	18.0	1.7	-	-	19.7	0.001
Armament - Ammo 500 x 20mm	394.0	38.1	-	-	432.1	0.028
- (2) M39 Guns	-	-	-	-	-	-
- Missiles	340.0	32.9	79.8	-	452.7	0.029
- Launchers	-	-	-	-	-	-
Equipment - O2, 5 Liters	-	-	-	-	-	-
- Survival Kit	-	-	-	-	-	-
- Misc.	140.0	13.6	-	-	153.6	0.010
<b>TOTAL USEFUL LOAD</b>	5,672.0	123.2	79.8	-	1,475.0	0.094
<b>Take-Off Gross Weight</b>	15,633.0	1,087.6	1,644.6	1,667.7	15,632.9	
4,400 lbs Fuel						

\*Given by:  $(\text{Empty Weight})_i / (\text{Zero Fuel Weight}) * (\text{Induced Drag Fuel Chargeability})$

\*\*Given by:  $(\text{Wave Drag})_i + (\text{Skin Friction Drag})_i$

\*\*\*Given by:  $(\text{Empty Weight})_i + (\text{Drag Fuel Ch.})_i + (\text{Prop. Fuel Ch.})_i$



**Figure 3: Comparison of Conventional Gross Weight Breakdown for the F-5E Versus Chargeable Gross Weight Breakdown.**

Once the breakdown of fuel cost chargeability is known, it is straightforward to incorporate this new information into existing models for operations costs and vehicle life cycle costs. In general, this merely requires that each component of chargeable fuel cost per trip be multiplied by the number of missions annually. The result is annual cost chargeable to each loss mechanism. This process can then be integrated forward through the expected life of the vehicle to obtain total cost chargeable to each loss over the life of the vehicle. Since the focus here is on thermodynamic loss and translation into weight chargeability, these aspects are somewhat beyond the intended scope of this paper. Therefore, further application of loss management models as a means of cost accounting is instead left as a topic for future development.

### **Comparison to Perturbation Methods**

The primary means used today to estimate the weight impact of thermodynamic performance are perturbation methods. Therefore, it is useful to compare perturbation results to those obtained using loss management models in order to obtain a better understanding of each. This subsection will focus specifically on comparisons for the most basic case for the F-5E. The similarities and differences between the results are described, and these three cases are used as an example to illustrate how the two methods provide complimentary information.

To understand how perturbation methods are used to estimate gross weight chargeability, consider a simple example case wherein the objective is to estimate gross weight chargeability due to fixed equipment weight. For instance, the hydraulics system weight of the F-5E is 153 lb. It may arise that one would like to know how much the hydraulic system weight actually contributes to gross weight. One approach to doing this is to delete hydraulics weight from the mission analysis model and re-run the analysis to estimate a new vehicle gross weight without the hydraulics system. The difference between the revised gross weight and the actual gross weight is then assumed to be due to the hydraulics system weight. In the case of the F-5E, the baseline gross weight is 15,633 lbs and the perturbed gross weight is 15,437 lbs, for a net delta of 196 lbs. Of this, 153 lbs is due to deletion of hydraulics weight, and 43 lb due to reduction in mission fuel.

However, in order to obtain this estimate, one *must* make several assumptions. In this case, it was assumed that the mission was unchanged, all vehicle other vehicle weight groups were held fixed, engine and wing size remained constant, and mission fuel was sized to complete the mission. A consequence of these assumptions is that the 43 lb reduction of mission fuel is not a savings due to only to reduced hydraulic systems weight. It is also due to empty weight interaction with the mission, specifically reduced engine losses because the vehicle can climb to altitude faster and spends less time in afterburning climb. Therefore, the 43 lb fuel reduction represents a *confounded effect* of several mechanisms that interact with hydraulic system weight.

One could attempt to eliminate this confounding effect by forcing the mission analysis to use the same climb schedule such that climb time is the same, but in this case climb thrust will have to be reduced to match the previous climb rate. Another option would be to reduce engine size (keep thrust loading constant) so that climb performance remains the same. However, both of these options will lead to reduced fuel burn due to two

factors: propulsion system effects (either smaller engine size or part power operation) as well as reduced induced drag. Consequently, perturbation methods can only determine the net effect of a change in vehicle weight, and this net effect is invariably confounded with other mechanisms that act simultaneously and are generally indistinguishable from one another.

Next, contrast this with the result for fuel chargeability obtained from the F-5E loss management model. The results of Table 5 for the work potential example indicate that 14.6 lbs of mission fuel are consumed to offset induced drag losses required to generate lift to support the weight of the hydraulic system, or roughly 33% of the perturbation estimate. This result was *analytically* estimated based on the laws of thermodynamics and an assumed FoM for work potential. At no time was it necessary to perturb or otherwise change the mission model to obtain this figure. Consequently, the resultant estimate of 14.6 lbs mission fuel is purely due to hydraulic systems weight, and is not confounded with any other effect.

This is the fundamental difference between the perturbation result and the loss management result: *the perturbation result gives an answer to a “what if” question, including the net effect of all relevant interactions, but does not yield information regarding any one effect. The loss management result is purely due to a single effect, and does yield an answer for net effect at the vehicle level.* Therefore, the two methods yield information that is largely complimentary, each negating weaknesses of the other.

It should be obvious that, as far as the mission perturbation and loss management methods are concerned, there is no difference between a pound of hydraulics system weight and a pound of any other empty weight group. Therefore, empty weight groups have the same ratio of gross weight to empty weight. This gives rise to an oft-used concept in mass properties engineering known as growth factor, which is defined as the change in gross weight due to the change in empty weight (Staton, 1996). It is essentially a sensitivity of gross weight to empty weight subject to a prescribed set of assumptions:

$$GF \equiv \frac{\partial GW}{\partial EW} \bigg|_{\substack{\text{Wing Size=Const.} \\ \text{Engine Size=Const.} \\ \text{No Interactions}}} \approx \frac{\Delta GW}{\Delta EW} = \frac{GW_{perturb.} - GW_{base}}{EW_{perturb.} - EW_{base}} \quad (32)$$

where GF is growth factor, GW is gross weight, and EW is empty weight. Growth factor is easily calculated using a standard mission analysis model by perturbing empty weight and re-running the mission analysis code, as suggested in equation 32. The subscript “perturb” denotes the perturbed mission analysis case, while subscript “base” denoted the baseline vehicle model.

The estimation of growth factor is always predicated on a set of assumptions as to how the vehicle is allowed to change when perturbed. The simplest assumption (and that used herein) is that engine & wing size are fixed, and the perturbed weight group has no interactions with other weight groups. This necessarily implies a change in vehicle performance for the perturbed configuration. Other common scenarios are: holding wing loading constant, holding thrust loading constant, allowing interactions with other weight groups, or some combination thereof. All of these scenarios generally yield higher estimates for growth factor than does the simple “fixed-fixed-fixed” assumption because empty weight interactions with wing size, engine size, and other weight groups tend to exacerbate the sensitivity of empty weight to gross weight.

A comparison of growth factors for the F-5E derived using perturbation methods and loss management methods is compared in Table 6. The loss management “growth factors” were estimated by simply dividing the chargeable gross weight of each functional group given in Table 5 by their respective empty weights. It is clear from the results of this table that the thrust work potential estimate on growth factor is less sensitive than the traditional perturbation-based estimate. Even so, there is a three-fold difference between the two due to mission interactions with the re-sized vehicle, primarily climb.

**Table 6: Comparison of Empty Weight “Growth Factors” for the F-5E Subsonic Area Intercept Mission.**

<i>“Growth Factor” Estimation Method</i>	<i>“Growth Factor” Estimate</i>
<i>Thrust Work Potential</i>	<i>1.097</i>
<i>Standard Perturbation Methods</i>	<i>1.283</i>

The differences in these estimates can be reconciled by considering the physical meaning of each. The perturbation estimate for growth factor is the physical change in vehicle size that would result from a change in vehicle weight, a ratio of differences between two closely related (but distinctly different) vehicles. The “growth factor” for the loss management estimates is physically the ratio of a component’s gross weight contribution to empty weight contribution. At no time was the vehicle model perturbed in any way. Thus, it is somewhat of a misnomer to refer to the thrust work potential estimate as “growth factors” because the vehicle did not “grow” in order to estimate it. Instead, the estimate reflects the *pure impact* of empty weight contribution to gross weight for a single vehicle, without any confounding interactions. Consequently, Table 6 is an “apples and oranges” comparison, but it is useful to illustrate the relationships between the classical methods and those proffered herein.

A much more detailed comparison of growth factor results for the F-5E is shown in Table 7. This table shows a group-by group comparison of the growth factor for each component. Note that all components contributing only empty weight (no drag or propulsive losses) have the same growth factor, while those components that influence vehicle drag or propulsion system efficiency have growth factors that are higher than the simple empty weight groups. Starting with the structure group, it is interesting that the components having the largest growth factor are the horizontal and vertical tail. The reason for this is that these components contribute high drag loss relative to their weight. However, since the empennage surfaces are small, their total contribution to gross weight is small, in spite of their high growth factor. The wing and body groups exhibit considerably lower growth factors, though they are still much higher than the basic empty weight growth factor.

Comparison of these results to the analogous results obtained using perturbation methods reveals that once again, the perturbation estimate on growth factor is considerably higher than that estimated using loss

**Table 7: Detailed Comparison of Thrust Work Potential and Classical Growth Factors for the F-5E Subsonic Area Intercept Mission.**

<i>Weight Group</i>	<i>WP Growth Factor</i>	<i>Perturbation Growth Factor</i>		<i>Thrust WP Growth Factor</i>	<i>Perturbation Growth Factor</i>
<b>Structure Group</b>	1.382	N/A	<b>Fixed Equipment</b>	1.097	1.283**
Wing Group	1.461	1.949*	Flight Controls Group	1.097	1.283**
Tail Group- Horizontal	2.048	2.852*	Auxiliary Power Plant Group	-	-
- Vertical	1.985	2.556*	Instrument Group	1.097	1.283**
Body Group	1.401	1.640*	Hyd. and Pneumatic Group	1.097	1.283**
Alighting Gear Group -Main	1.097	1.283**	Electrical Group	1.097	1.283**
-Nose	-	-	Avionics Group	1.097	1.283**
-Arrest	-	-	Armament Group	1.097	1.283**
Engine Section or Nacelle Group	1.097	1.283**	Furnishings Group	1.097	1.283**
Air Induction System	-	-	Air Conditioning Group	1.097	1.283**
			Handling Group	1.097	1.283**
<b>Propulsion Group</b>	1.965	N/A			
Engine (As Installed)	2.356	1.991***	<b>TOTAL WEIGHT EMPTY</b>	1.097	1.283**
Gear Boxes and Drives	1.097	1.283**			
Exhaust System	-	-	Crew	1.097	1.283**
Cooling and Drain Provisions	-	-	Fuel - Unusable	1.097	1.283**
Engine Controls	-	-	Fuel - Usable	-	-
Starting System	-	-	Oil - Engine	1.097	1.283**
Fuel System	1.097	1.283**	Armament - Ammo 500 x 20mm:	1.097	1.283**
			- (2) M39 Guns	-	-
			- Missiles	1.332	1.497*

*Assumptions:*

F-5E, Subsonic Area Intercept Mission  
Fixed Engine Size, Fixed Wing Size

\*Estimated by Deleting Component Drag & Weight and Re-Running Mission Analysis

\*\*Estimated by Deleting Component Weight and Re-Running Mission Analysis

\*\*\*Estimated by Deleting Engine Weight & Component Losses and Re-Running Mission Analysis

management techniques, ostensibly due to interactions with the mission. However, all the trends are completely consistent between the various techniques in terms of relative magnitudes, with empennage growth factors being the most sensitive, followed by wing and fuselage growth factors.

Examination of the propulsion system growth factor shows that it is most sensitive for thrust work potential and least sensitive for the perturbation estimate. This trend makes sense in that thermodynamic loss in the propulsion system is high, so the propulsion system therefore receives considerable fuel chargeability. Likewise, growth factor is sensitive to propulsion system performance for this same reason. If these results are compared to the perturbation estimate, the trends are once again consistent with what one would expect.

It should be noted that the perturbation estimates for growth factor shown in this table have been obtained by deleting the component weight and drag, as appropriate, and re-running the mission analysis case to obtain a change in gross weight and thus, a gross weight sensitivity. The perturbation estimates are not entirely consistent with the classical definition of growth factor as it is ordinarily used in mass properties engineering. Rather, they are a perturbation estimate on overall gross weight impact due to a single component.

## **Technology Evaluation Via Loss Management Models**

Integration and evaluation of advanced technology in tomorrow's highly complex and integrated vehicles is one of the most formidable tasks facing designers today. Technology integration is inherently a multidisciplinary problem requiring tremendous depth and breadth of knowledge to accomplish. Moreover, it is difficult to ascertain the true benefits of any individual technology when employed as part of a suite of advanced technologies installed in an advanced design or concept demonstrator. This is due to the interactions amongst the technologies and because there is seldom a common figure of merit that captures both the weight and performance impact of any given technology.

Based on the development presented to this point, it should be clear that loss management models have considerable potential to facilitate evaluation and selection of those technologies that impact vehicle aerothermodynamic performance and/or weight. Specifically, the concept of gross weight chargeability can provide an integrated framework for multidisciplinary design wherein the aerothermodynamic cost and benefit of technology concepts can be explicitly evaluated. In effect, chargeable gross weight is a common measure for comparison of disparate performance metrics and technologies.

As a simple example of how loss management models can be used to evaluate the impact of advanced technologies on vehicle chargeable gross weight, consider a hypothetical advanced technology derivative of the F-5E. One technology that shows strong promise for application on future fighter aircraft is the active aeroelastic wing (AAW). The concept behind AAW is to use the natural flexibility of the wing to improve control authority while reducing wing weight. This is done by tailoring the wing structure and control surfaces such that a control surface deflection produces a proverse deflection in the wing. In effect, the control surfaces act like servotabs and the entire wing becomes a control surface. The net result is increased control effectiveness using smaller control surfaces and/or a reduction in wing weight due to relaxation of wing stiffness requirements.

Suppose for argument's sake that the F-5E is re-winged with an AAW of slightly higher aspect ratio and reduced stiffness such that the wing weight is reduced by 20% relative to the original F-5E wing. Further assume that the aspect ratio change is sufficient to reduce induced drag by 10%. However, increased aspect ratio will also drive supersonic wave drag up due to decreased span loading. The increase in wave drag is usually evaluated at the preliminary design level using a far-field wave drag estimate, but in this case, it is assumed that the increased span loading causes a 10% increase in supersonic wave drag.

If the re-winged F-5E is "flown" through the design mission (assuming fixed mission fuel of 4,400 lbs) using standard mission analysis techniques, the result is a revised estimate on combat radius, as shown on the left side of Table 8. Mission analysis shows that the AAW increases combat radius by 47 nmi or 21% over the baseline F-5E wing. In addition, it is clear from the left side of Table 8 that much less fuel is burned in climb to combat altitude. This is because the reduction in weight and drag due to the AAW tends to increase climb rate.

Therefore the fuel that was otherwise used in afterburning climb is instead used during subsonic cruise for the AAW-enabled concept. Also note that the AAW wing yields a modest reduction in reserve loiter fuel consumption. Finally, the empty weight breakdown at the bottom left of Table 8 shows that the AAW concept reduces wing weight by 263 lbs.

This information is useful, but it does not yield any insight as to what are the fundamental mechanisms driving the differences. This is precisely the information that loss management methods can provide, as shown in the right side of Table 8. First, the upper right portion of this table shows how chargeable fuel weight changed between the baseline and the AAW-enabled case. Note that fuel weight chargeable to wave drag increased, while fuel weight chargeable to induced drag decreased, as one would expect. However, it is surprising to note that fuel weight chargeable to afterburner losses increased while that due to compressor losses decreased. This is primarily due to the differences in the climb and dash profile previously noted.

If the chargeable mission fuel weight is added to group empty weights, the result is chargeable gross weight, shown at the lower right of Table 8. It is not surprising that the AAW reduces wing chargeable weight by 278 lbs, though it is interesting that chargeable weight for the tail and body groups increases. This may at first seem counterintuitive, but upon deeper reflection, the reason for the increase is clear. Total mission fuel is fixed, so as the wing becomes increasingly efficient, the other functional groups will receive a larger share of fuel weight chargeability. This is also reflected in the propulsion system chargeable gross weight, which increases by 46

**Table 8: Comparison of Classical and Loss Management Results for a Re-Wing Scenario on the F-5E.**

<i>Standard Analysis Methods</i>				<i>Loss management Analysis</i>			
	<i>Baseline F-5E</i>	<i>AAW F-5E</i>			<i>Baseline F-5E (lb fuel)</i>	<i>AAW F-5E (lb fuel)</i>	
Combat Radius	225 nmi	272 nmi		Fuel Chargeability			Delta
	Fuel Burn	Fuel Burn		Stores Drag	156.1	159.7	3.6
Mission Leg	(lmb)	(lmb)	Delta	Fus. Wave Drag	164.3	309.4	145.2
Taxi Out	0	0	0	Wing Wave Drag	36.7	69.2	32.5
Take Off	351	351	0	Tail Wave Drag	15.0	28.4	13.4
Accelerate	227	221	-6	Fus. Skfr. Drag	573.7	568.8	-4.9
Climb	422	428	6	Wing Skfr. Drag	433.5	429.8	-3.7
Cruise	326	596	270	Tail Skfr. Drag	267.5	265.4	-2.0
Climb to Combat Alt	791	530	-261	Induced Drag	1148.6	851.6	-297.0
Dash	316	227	-89	Afterbody Drag	30.8	34.6	3.8
Combat	528	528	0	Spillage Drag	64.7	65.3	0.6
Cruise Back	698	799	101	Inlet Recovery	144.1	171.8	27.8
Reserve Loiter	521	500	-21	Compressor Efficiency	409.8	321.9	-87.8
Reserve Fuel (5%)	220	220	0	Combustor Press. Drop	96.5	84.2	-12.4
Taxi In	0	0	0	Turbine Efficiency	253.4	241.1	-12.2
Total Fuel	4400	4400		A/B Comb. Eff.	95.7	237.3	141.6
				Nozzle CFG	70.3	108.3	38.0
				Other	439.5	453.2	13.7
<i>Empty Weight Breakdown</i>				<i>Chargeable Gross Weight Breakdown</i>			
Wing Group	1315	1052	-263	Wing Group	1921	1643	-277.9
Tail Group- Horizontal	306	306	0	Tail Group	618	629	11.2
Body Group	2648	2648	0	Body Group	3709	3751	42.1
Lighting Gear Group	765	765	0	Lighting Gear Group	839	826	-13.6
Engine Section	174	174	0	Engine Section	494	486	-8.0
Air Induction System	276	276	0	Air Induction System	-	-	-
Structure Group	5484	5221	-263	Structure Group	7581	7334	-246.1
Propulsion Group	1922	1922	0	Propulsion Group	3776	3822	46.4
Fixed Equipment	2555	2555	0	Fixed Equipment	2802	2757	-44.8
Total Weight Empty	9961	9698	-263	Total Weight Empty	14159	13914	-244.5
Total Useful Load	5672	5672	0	Total Useful Load	1474	1456	-18.4
Takeoff Gross Weight	15633	15370	-263	Takeoff Gross Weight	15633	15370	-263

lbs. Fixed equipment and useful load gross weight chargeability decrease because the reduction in induced drag ameliorates the thermodynamic penalty of vehicle fixed weight, thereby reducing chargeable fuel weight for fixed equipment and useful load weight groups.

In summary, the standard mission analysis reveals that the AAW-enabled F-5E in this example has a 21% increased combat radius, primarily through reduction in losses incurred during afterburning climb. The loss management analysis reveals a detailed accounting of *why* and *how* mission fuel chargeability changes amongst the various functional components due to the addition of an AAW. It is shown that an AAW not only leads to decreased wing gross weight chargeability, but also increases propulsion system and fuselage gross weight chargeability, thereby making it more attractive to incorporate advanced propulsion and fuselage structural technologies in future updates of the airframe. This analysis offers, for the first time, the ability to create a comprehensive and consistent picture of vehicle aerothermodynamic performance in terms of vehicle gross weight. The results of this analysis can be used to directly compare the aerothermodynamic impact of technology concepts and yields not only a better understanding of the underlying mechanisms driving the changes, but also a *unified picture* of overall impact.

## Conclusions

Just as a viable country must have a national unit of currency to measure the value of goods and facilitate trade, so must the vehicle designer have a unit of currency to measure the value of design choices. In effect, *loss management methods use vehicle chargeable gross weight as a unit of “currency” to measure design value.* This paper has focused on developing and demonstrating this fundamental idea by linking fuel flow rate to thermodynamic performance through the concept of ideal work per unit mass of fuel. It is intuitively obvious that there is a relationship between fuel weight and thermodynamic performance, *yet it represents a considerable departure from today’s thinking.* This concept of chargeable gross weight has the power to bring many of the most important aspects of vehicle preliminary design under a common umbrella by providing a universal framework in which the relative merits of dissimilar design trades can be readily compared.

This paper began with a development and explanation of the theoretical underpinnings for a generalized model of work potential applicable to *all* vehicles. This was then implemented as part of a larger aircraft loss management methodology and demonstrated for the F-5E. Not only does this technique provide a means of *analytically* estimating gross weight chargeability, but can also be used to determine fuel *cost* chargeability. This is a capability that, for all practical purposes, does *not* currently exist. When chargeable fuel costs are integrated through the life of the vehicle, the result is a detailed picture of the dollar cost of *each and every* source of thermodynamic loss relevant to the vehicle’s operation.

It was shown that perturbation methods cannot yield information about the weight chargeability of the baseline vehicle itself, only the net effect of perturbations therefrom. On the other hand, loss management methods yield information on the unconfounded gross weight chargeability, but cannot by itself yield information on the net effect of a vehicle modification because it uses information from only a single vehicle model. In spite of these differences, the trends exhibited by these various measures of growth factor are consistent in terms of relative magnitude.

Calculation of fuel chargeable to each loss is accomplished based on pure thermodynamics. However, it is worth reiterating that the distribution of fuel chargeability amongst functional components is merely a bookkeeping scheme. The chargeability scheme presented for the F-5E is only one of many possible valid schemes, and the choice of how to apportion chargeability is decided largely on the basis of what best suits the needs for the problem at hand. Furthermore, the F-5E example focused on defining chargeability for first order drivers on vehicle weight. However, this model could easily be refined to account for second-order effects.

One of the chief strengths of the method espoused in this paper is that it would enable all functional groups to track a single, *consistent* system-level FoM. This is a powerful tool to focus the efforts of a diverse group of designers each having differing points of view and design objectives. For instance, the engineers designing the landing gear of an aircraft will have vastly different objectives from the engineers doing the wing aerodynamic design. However, if each of their contributions can be quantified in terms of chargeable gross weight, then one



has an “apples-to-apples” comparison of how much each group contributes to gross weight and how much each can be improved upon. Additionally, such an approach focuses all attention on a single objective: keeping chargeable gross weight to a minimum.

## Acknowledgements

The authors would like to thank the National Science Foundation for supporting portions of this work under grant DMI 9734234. In addition, we would like to thank our many friends and co-workers at Georgia Tech ASDL and at General Electric Aircraft Engines who have contributed to this work in subtle but important ways.

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